

A simplified equivalent circuit model for simulation of Pb–acid batteries at load for energy storage application

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ABSTRACT

Three main types of battery chemistries in consideration for vehicle applications are Pb–acid, nickel–metal hydride, and lithium-ion batteries. Lead–acid batteries are widely used in traditional automotive applications for many years. Higher voltage, high-rate discharge capability, good specific energy, lower temperature performance, lower thermal management requirement, and low-cost in both manufacturing and recycling are the advantages of the rechargeable battery. Disadvantages of the lead–acid battery are: weight concerns of lead metal (lower energy density and lower power density) and limited cycle-life (especially in deep-cycle duties). If two major disadvantages have been significantly changed to a proper state to compete with other battery chemistries, the Pb–acid battery is still a good candidate in considering of cost/performance ratio. The lead–acid battery is always a good power source for fast starting of cold vehicles, for recharging from either a stop-start braking system, or for a charge from the engine itself, which consumes battery energy or stores electricity back into chemical energy. The main reasons for reexamining this battery chemistry are cost-savings and life-cycling considerations upon advances in electrode structure design and enhancement of capacitance behavior inside the battery pack. Several Pb–acid batteries were evaluated and tested through a unique method, *i.e.*, the electrochemical impedance method at different loads, in order to characterize and further understand the improved electrode processes and mechanisms in performance enhancement. The impedance data at loads were collected from these lead–acid batteries at load for further analysis. Battery electrode behaviors are evaluated through impedance data simulation using a proper equivalent circuit model. A defective battery and a failed Pb–acid battery were used in non-destructive analysis. The recent Pb–acid battery advancement in structures and designs and its potential application are also discussed for power reserve in energy-efficient vehicles and sustainable electricity storage.

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1. Introduction

Lead–acid, nickel–metal hydride, and lithium-ion are three types of battery chemistries for potential EV and HEV applications [1,2]. Lead–acid batteries have been widely used as secondary battery for more than a 100 years. The advantages of the lead–acid system are its high-rate discharge capability, good specific energy, high reliability, robustness, low-cost in both manufacturing and recycling as the battery is manufactured mainly from a single low-cost raw material [3,4]. Furkawa et al. [5–7] developed a Pb–acid ultrabattery prototype within a single battery casing. The ultrabattery is an integrated hybrid energy device which combines features of lead–acid battery and supercapacitor. The valve-regulated ultrabattery is designed specifically for hybrid-electric vehicle (HEV) duty, *i.e.* high-rate partial-state-of-charge operation (HRPSoc). Firefly Energy [8] developed a deep-cycle

absorbed-glass-mat (AGM) Pb–acid battery that employs Microcell™ foam technology. The battery is designed for repeated deep discharges and high power applications in which maximum run times are needed to very low depths of discharge. EnerSys Energy [9] fabricated Odyssey® lead–acid batteries. This type of lead–acid battery provides enormous cranking power and deep-cycle capability. Although many researchers and government agencies paid more attention on other battery chemistries rather than the conventional lead–acid battery, a few Pb–acid battery breakthroughs in new electrode structure, rate and deep-cycle performance have been made due to the strong needs for development of low-cost energy-saving systems and low-emission vehicles.

Electrochemical impedance spectroscopy (EIS) is an excellent tool to analyze the interfacial process, variation in the internal resistance, state-of-charge, and the residual capacity of a lead–acid battery. The *ac* impedance method is a fast, accurate, and non-destructive in nature for the modeling and diagnosis of industrial batteries [10]. The basic experiment of the EIS method consists in applying a small, sinusoidal voltage or current signal to an

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electrochemical cell, measuring the system's response with respect to amplitude and phase, and determining the impedance of the system at a certain range of different frequencies. Interpretation of the results and proper modeling requires that the experimental setup allows some idealization like separating between working electrode and the reference electrode or maintain the concentrations of reactants essentially constant at the interface [11]. The impedance technique can be applied to dynamic modeling of battery behavior and diagnosis of quantities like actual capacity, state-of-charge (SoC) and state-of-health (SoH) [12]. Diard et al. [13,14] conducted a general EIS study on electrochemical battery discharge at a constant load and constant current and its emphasis was on the impedance test for a lead–acid battery with high capacity and low impedance at load. Pavlov and Petkova [15] investigated the mechanism of the positive plate in a lead–acid battery via *ac* impedance. Its purpose was to establish the mechanism of the processes that proceed during discharge and cycling of the lead dioxide plate in the lead–acid battery. Kirchev et al. [16] examined the pulse charge of the lead–acid battery, and paid a special attention to the impedance spectrum of the positive plate as a source for estimation of the electrostatic capacitance of the double layer (C_{dl}) on the surface of the positive active mass. The SoH influences mostly the ohmic resistance, the charge transfer resistance R_{ct} and the parameters of the constant phase element accounting the diffusion in the pores when the plate is well charged.

Battery modeling is an important issue for design of different battery applications. It is necessary to develop a reliable and easy-to-parameterized battery model. However, for the lead–acid battery, the impedance spectra depend very much on the short-term charge–discharge history. Karden et al. [12,17] further discussed methodological questions connected with the measurement and interpretation of the impedance of batteries, especially nonlinearity, voltage drift, stability, reproducibility, half-cell measurements, model structure, and parameter extraction from the impedance data. Blanke et al. [18] reviewed different approaches to determine SoC, SoH, and cranking capability of lead–acid batteries. The methods and procedures aimed for a reliable prediction of battery performance. The purpose of this work is to use a unique impedance method to test lead–acid batteries at different loads for better understanding of Pb–acid battery specific structures, mass transfer processes in the electrodes and rate-limiting steps in the electrochemical reactions. Testing, analysis and appropriate impedance simulation are given in order to develop a wide range design tool or a proper model for dynamic applications of the advanced lead–acid battery, especially in various power reserve needs.

2. Experimental

For performance improvement of the lead–acid battery, the basic idea is to increase electrode surface area, optimize the internal design (active material, supporting structure, electrolyte, separator, and gas recombination), and enhance the system maintenance such as thermal management. Several types of lead–acid batteries were employed in this work. One AGN-8 Pb–acid battery was defective and taken out from a Toyota Camry after 8-years starting/lightening/ignition (SLI) service in vehicle. Another battery (BDU-S) was at standby mode for *ca.* 8 years, which was occasionally charged for maintenance purpose. The third battery (CDU-N) was purchased from a local part store for replacement of the AGN-8 battery. The above three batteries are several common batteries for SLI applications on the market. The conventional battery design only provides high amperage discharges for engine starting applications. The fourth lead–acid battery (ODY-N) is an advanced battery which provides double cranking power in comparison with the conventional ones. The battery can be cycled for 400

charge–discharge cycles at 80% DoD (depth of discharge). It uses rugged construction and AGM (absorbed-glass-mat) separator structure. Unlike traditional batteries that need a recharge every 6–12 weeks, the thinner-plate design and fabrication of the ODY-N battery allow the fully charged battery lasting up three times long and can be stored up to 2 years with capable of full power restoration. The AGM dry cell design holds acid in place and prevents acid spills. Its cranking power is double to triple that of equally sized conventional batteries, even when the temperature is as low as -40°F . The ODY-N battery belongs to valve-regulated lead–acid (VRLA) technology and its starved electrolyte design allows the battery shipped easily. The fully charged battery normally has an open circuit voltage of 12.65 V. The above mentioned battery parameters are listed in Table 1.

The Gamry FC350™ system (Gamry Instruments, Inc., Warminster, PA) with an electronic load is available to work at a higher current range for measuring *ac* impedance data. The sinusoidal current signal from the Gamry system, working in the hybrid-impedance mode, modulated the current from the lead–acid battery pack. The experimental schematic of the battery impedance test is shown in Fig. 1, including the above impedance system, an electronic load and lead–acid batteries. Traditional measurements are performed using constant RMS (root mean square) amplitude for the *ac* signal. The problem with this technique is that the impedance of the cell varies significantly from high to low frequencies. For impedance to be accurate, the perturbation signal has to be sufficiently small to maintain a pseudo-linear *i*–*V* operation. Hybrid measurements compensate for the change in cell impedance as frequency is varied by changing the *ac* current amplitude to keep measured *ac* voltage at a set of value. The previously measured impedance point is used in determining the new current amplitude, as the scan proceeds from 10 kHz to 10 μHz. In this work, the hybrid EIS mode was applied for the experiments in order to observe the EIS behavior at various frequencies. For the impedance spectrum, the non-linear least squares fitting algorithm was applied to find the model parameters for best agreement between the model impedance spectra and the measured spectra. The amount of consumed energy of the lead–acid battery was approximately charged back after each impedance measurement and then fully charged overnight at a current of less than 1.00 A with a voltage no more than 13.5 V. After the battery was ready for impedance test, the Gamry system with an electronic load, working in hybrid-impedance mode, modulated the current from the battery at load. Simultaneously, the current information at the electronic load was sent to a computer monitor. The Gamry system collects these testing data and generates the impedance data files. Better results on impedance analysis at a high power output can be obtained using this impedance system.

3. Results and discussion

Impedance-based battery models are essential to the simulation of the complexity of modern power electronics. Battery behaviors are highly non-linear and their dynamic performance depends on different parameters such as temperature, service life-time, and state-of-charge. Electrochemical impedance spectroscopy is a unique tool to obtain useful physical and chemical parameters for different battery models. Small-signal excitation and evaluation of the battery system response enable accurate simulations at nearly any working point. A typical impedance spectrum of a lead–acid battery is shown in Fig. 2. The impedance data related to the anode surface appears as a small semicircle at the high frequency side on the battery impedance spectrum. It constitutes a small contribution to the overall impedance [19]. The cathode electrode process dominates the larger impedance spectrum at the low frequency side. Porous PbO_2 is formed during charging and has high conduc-

Table 1

Technical data of different types of 12 V lead–acid batteries.

Pb–acid battery	Part number	Cold cranking current (A)	Nominal capacity	Battery condition	Note
AGN-8	28800-AA041	582	–(RCMs ^a ≥ 125 min)	In Toyota Camry for ca. 8 years	(a) One day failed to start up the car (b) It was tested at a battery store and the result showed that it was a bad battery (10–12 V at load is good)
BDU-S	51-D	500	85 Ah	Standby mode for ca. 8 years	Not put in the normal use, charged occasionally
CDU-N	24F-DL	600	110 Ah	New from battery store	The new battery replaced the AGN-8 battery
ODY-N	34/78-PC1500	880	68 Ah (135 min)	New bought from online store	Fully charged before shipment

^a Reserve capacity minutes (RCMs) are the time that a new, fully charged battery will deliver 25 amperes at 80 °F and maintain a terminal voltage equal to, or greater than, 1.75 V per cell. This rating represents the time the battery will continue to operate essential accessories if the alternator or generator of a vehicle fails. Put another way, reserve capacity is a battery's ability to sustain a minimum vehicle electrical load in the event of a charging system failure.

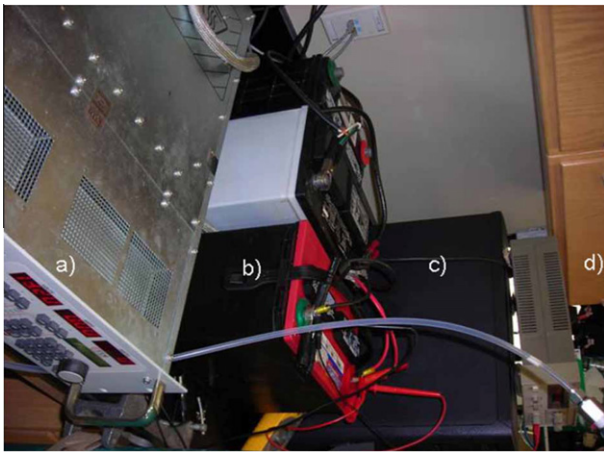


Fig. 1. Lab test system for lead–acid batteries using a Gamry impedance system with an electronic load: (a) electronic load; (b) Pb–acid batteries; (c) Gamry impedance system; (d) power supply for battery charge.

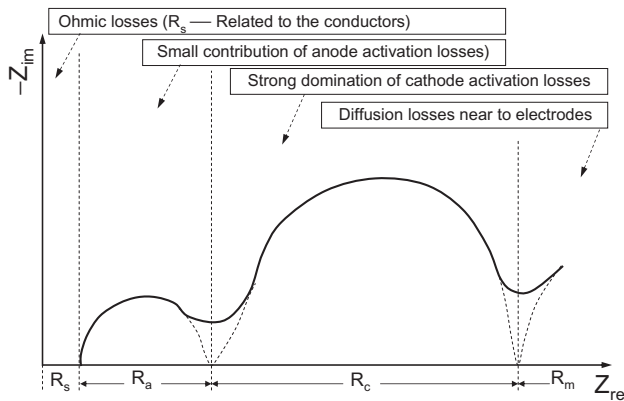


Fig. 2. Schematic drawing of typical impedance spectrum of a lead–acid battery.

tivity for metal oxide, and yet much lower conductivity than lead metal [20]. This explains the higher impedance of the cathode, which is shown as larger semi loop near low frequency side (Fig. 2). At the right side of the impedance plot, a short impedance line is also observed during Pb–acid battery tests. This appears to be contributed by the diffusion process outside of the electrodes. The further simulation on the impedance data are included and discussed in the following sections.

3.1. Conventional lead–acid batteries

Four lead–acid batteries were set up and fully charged before collecting their impedance data. Fig. 3 shows Bode plots from impedance data of two Pb–acid batteries. Because of the high concentration of the ions taking part in charge/discharge reactions in the Pb–acid battery, the impedance is negligible for liquid electrolyte and its influence only appears in the high frequency region as a series resistance. The ohmic resistance is ca. 0.004 Ω for the CDU-N battery and ca. 0.007 Ω for the BDU-S battery. The battery Nyquist plots are obtained at 5 A initial current as shown in Fig. 4. The half-semicolon at the low frequency side has a different shape after years of service in automobile or at standby mode. The new CDU-N battery has a depressed semicircle at low frequency side. The depressed semicircle reveals that the cathode side ($\text{PbO}_2/\text{PbSO}_4$) needs a further formation process to become a well functioned electrode because the lead oxide electrode has some paste additives such as plastic fibers for enhancing its mechanical strength of the dried paste [21]. After the battery was well soaked and formed in the H_2SO_4 electrolyte, the impedance spectrum of the BDU-S battery related to the cathode has a better semicircle shape. The semicircle on the left side of high frequency region (Fig. 4) is related to the impedance of the Pb/PbSO_4 anode surface and electrode reaction process [20]. Based on the test results, the small anode semicircle loop appears to grow larger after the AGN-8 battery worked in the vehicle for 8 years. The series ohmic resistance was also much larger than that of new CDU-N and ODY-N batteries at load. This evidence shows that its anode has an improved capacitance behavior but with increased series resistance. A circuit diagram as shown in Fig. 5 is chosen to

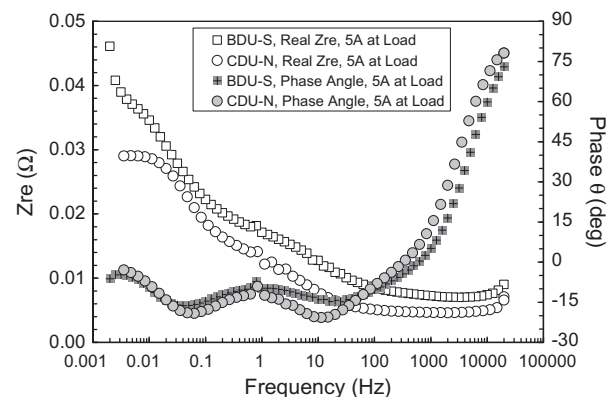


Fig. 3. Bode plots from impedance data of two Pb–acid batteries with initial loading of 5 A current.

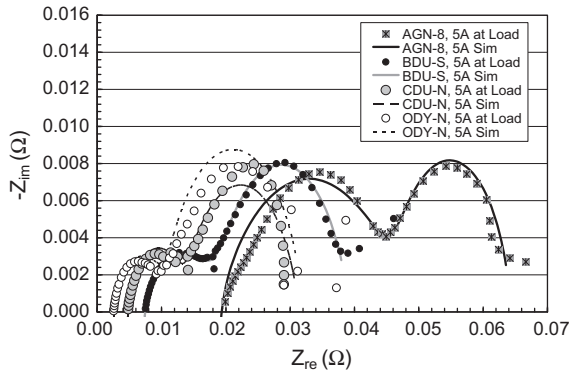


Fig. 4. Nyquist plots from impedance data of four Pb-acid batteries with initial loading of 5 A current.

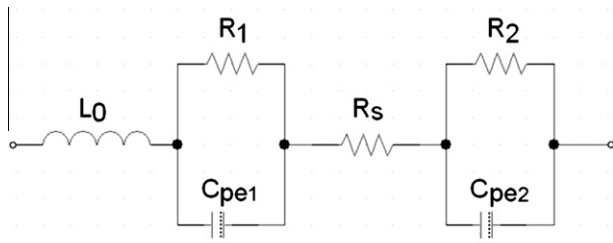


Fig. 5. A simplified equivalent circuit diagram for simulation of impedance data of a Pb-acid battery. L_0 represents small inductance due to wires and contact resistance; R_s represents series resistance; R_1 and R_2 represent anode and cathode charge transfer resistance, respectively; C_{pe1} and C_{pe2} represent anode and cathode constant phase elements, respectively.

simulate the collected impedance data points. The symbol of C_{pe} is called as constant phase element – replacement of double layer capacitor in considering of electrode roughness or heterogeneous reaction rates with varying activation energies on a surface (e.g., porous electrodes with a distribution of active sites). The symbol of C_{pe} includes two parameters, α and Y_0 . The values of simulated physical elements are listed in Table 2. The simulated results are well matched with the measured impedance data, especially for the AGN-8 and BDU-S batteries. There are some difference between data and simulated values for the new batteries. This is likely caused by the battery formation process. It takes time to have the electrodes well formed and makes the electrode oxidation and reduction processes more smoothly. The test results reveal that shape and location changes of the frequency loops are related to battery electrode performance and power reserve capability.

3.2. Flat plate Pb-acid battery

The ODY-N battery was fabricated with thinner flat plates made of 99.99% pure virgin lead. More electrode surface area means more reserved battery power. The improved design increases the cranking pulse up to 2250 amps for 5 s. The ODY-N battery uses dry cell AGM technology to hold acid electrolyte which is the same as many popular spiral-wound batteries. But the ODY-N battery employs flat plate design and provides 15% more plate surface area than the spiral wound battery structure [1,22]. The tested and simulated results for the ODY-N battery are shown in Fig. 6. Nyquist plots are obtained at different current levels. Impedance modeling uses the same equivalent circuit of $LR(RC_{pe})(RC_{pe})$ for the curve fittings. It is not clear that the simulated curve at a 1.00 A initial load has some difference in comparison with the tested impedance data at the right side of two continuous frequency loops. One reason appears to be the starved electrolyte design, i.e. dry cell AGM tech-

nology. This results from electrolyte mass transfer limitations because more sulphuric acid needs at the cathode side during discharge (One PbO_2 needs $2H^+$ at the positive electrode during discharge). At higher current levels, the tested impedance data points digress away from the normal loop curves near the low frequency semicircle. Hawkins and Barling [23] indicated that the impedance increase during discharge is dominated by the PbO_2 porous layer in the low frequency region. This also indicates that mass transport limitation happens inside the cathode electrodes ($PbO_2/PbSO_4$) because the acid electrolyte is starved in the AGM structure. The phenomenon of mass transport limitation reveals that the electrolyte transfer process affects the reaction in the $PbO_2/PbSO_4$ electrode.

3.3. Non-destructive analysis of defective lead-acid battery

The AGN-8 battery failed to start a Toyota car after ca. 8 years of service. The battery was removed from the vehicle, fully charged, and then impedance data were collected. Its Nyquist plots are shown in Fig. 7. In comparison with the new ODY-N battery ($R_\Omega = 0.0025 \Omega$) and the CDU-N battery ($R_\Omega = 0.004 \Omega$), the ohmic resistance for the AGN-8 battery is increased to ca. 0.020Ω after a service of ca. 8 years. The frequency loops are obviously different from other batteries at the high frequency side. However, the simulated curves using $LR(RC_{pe})(RC_{pe})$ circuit diagram are well fitted with the measured impedance data, especially at 1A initial load current. The change of the anode surface ($Pb/PbSO_4$) appears to be the main reason for shape change at the high frequency side. Efforts [5,6] have been made to overcome this performance degradation by attaching a carbon capacitor plate to the negative plate ($Pb/PbSO_4$). The task for the negative electrode is greatly reduced but the battery rate performance and pulse charge/discharge capability is enhanced due to the enhanced capacitance behavior of the attached electrode.

The BDU-S battery was failed to operate at 12 V output level because it was not charged back in time after an impedance test (Fig. 8). In comparison with the defective AGN-8 battery, the voltage of BDU-S battery is ca. 1.90 V less than the AGN-8 battery after 10 min discharge at 1.0 A current. It is concluded that one cell is failed in the BDU-S battery. The normal Nyquist plot is obtained at ca. 12.17 V before battery failure as shown in Fig. 9. But after it was failed to charge back in time, the Nyquist plot turns to be abnormal in comparison with a healthy battery such as the ODY-N battery. The small loop at high frequency region is disappeared after the battery voltage is reduced to no more than 11.51 V. This reveals that the negative electrode ($Pb/PbSO_4$) is failed with very poor charge retention due to the anode surface sulfation. The further work may study the degradation mechanism and look for an alternative way to reduce the anode degradation and improve the battery rate performance.

3.4. Novel structure design and potential power reserve application of Pb-acid batteries

Future batteries for vehicle applications of electric vehicles (EVs) and hybrid-electric vehicles (HEVs) require the development of deep-cycle long-life EV batteries and high-rate long-life HEV batteries. Flat thin-plate structures have been made progress for deep-cycle requirement and cranking power needs. Rurukawa and Lam [5,6] developed a unique structure for the lead-acid battery, called as 'ultrabattery.' It is a hybrid energy device where a lead-acid battery and an asymmetric capacitor are integrated into one conventional Pb-acid battery. The embedded capacitor enhances the battery charge/discharge performance for vehicle and pulse power applications. The total current on the negative plate is the sum of the capacitor current and lead-acid negative

Table 2
Values of simulated physical elements at different loads.

Initial load current at test	Physical elements	Values of simulated elements in the circuit diagram			
		BDU-S battery	CDU-N battery	AGN-8 battery	ODY-N battery
1 A	R_s (Ω)	0.007508	0.004693	0.0172	0.0025
	R_1 (Ω)	0.01245	0.0088	0.07092	0.0141
	R_2 (Ω)	0.08137	0.1209	0.08856	0.0904
	Y_{01} ($S s^{1/2}$)	9.09	2.503	4.585	9.6100
	α_1	0.5367	0.7852	0.4579	0.7762
	Y_{02} ($S s^{1/2}$)	110.5	61.90	531.1	190.0
	α_2	0.786	0.5805	1.000	0.7747
	L_0 (H)	1.69E-07	2.325E-07	2.85E-07	1.79E-07
5 A	R_s (Ω)	0.006857	0.00456	0.018	0.0023
	R_1 (Ω)	0.01232	0.00912	0.02931	0.0080
	R_2 (Ω)	0.02002	0.01765	0.01703	0.0247
	Y_{01} ($S s^{1/2}$)	10.77	4.390	3.16	8.7970
	α_1	0.5666	0.7834	0.5769	0.7590
	Y_{02} ($S s^{1/2}$)	351.2	148.1	367.6	224.80
	α_2	0.828	0.8272	0.920	0.7097
	L_0 (H)	1.986E-07	2.14E-07	2.675E-07	1.808E-07
10 A	R_s (Ω)	0.007259	0.00442	0.01761	0.00227
	R_1 (Ω)	0.008919	0.007148	0.0199	0.005983
	R_2 (Ω)	0.01148	0.01219	0.01091	0.0131
	Y_{01} ($S s^{1/2}$)	8.404	2.84	3.467	2.60
	α_1	0.5821	0.7085	0.5610	0.7439
	Y_{02} ($S s^{1/2}$)	191.5	81.40	381.3	169
	α_2	0.8018	0.7962	0.8775	0.7093
	L_0 (H)	2.07E-07	2.424E-07	2.68E-07	2.16E-07

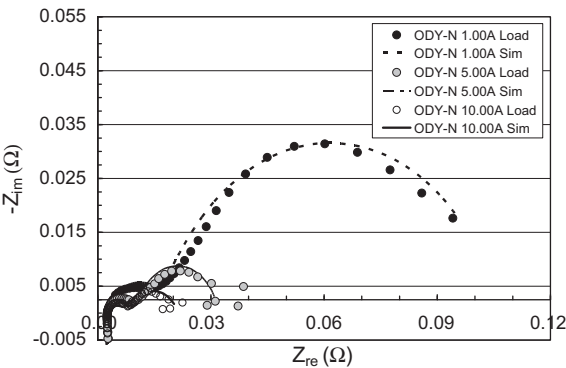


Fig. 6. Nyquist plots of the ODY-N Pb-acid battery at different current levels. Simulated curves using LR(RC_{pe})(RC_{pe}) circuit diagram.

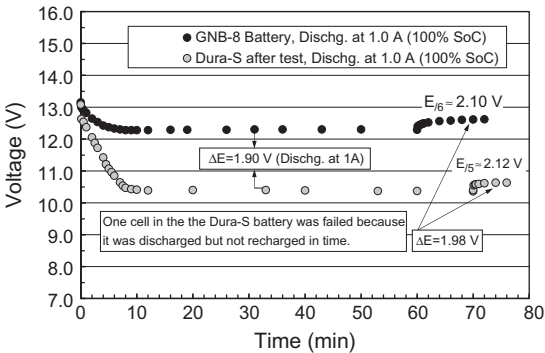


Fig. 8. Battery voltage as a function of time. One cell in the BDU-S Pb-acid battery was failed after it was discharged but not recharged in time.

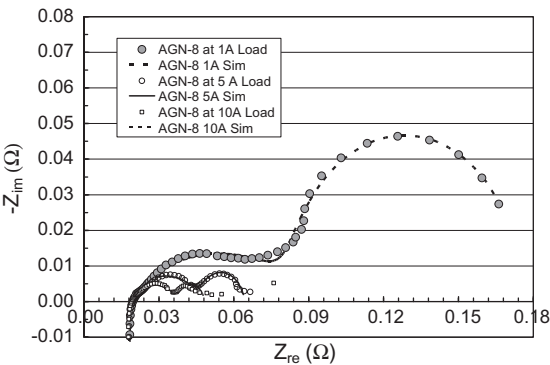


Fig. 7. Nyquist plots of the AGN-8 battery at different current levels. Simulated curves using LR(RC_{pe})(RC_{pe}) circuit diagram.

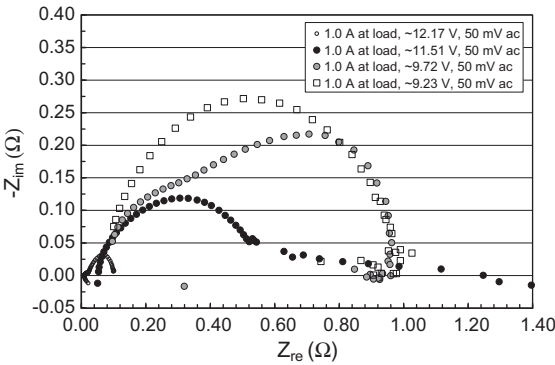


Fig. 9. Nyquist plots from impedance data of the BDU-S Pb-acid battery with initial loading of 1 A current.

plate current. The R&D results [24] show that the ultrabattery design is four time longer than that of the conventional battery

using for partial state-of-charge (PSoc) and rapid charge/discharge cycles. This hybrid design is suitable for HEV applications. Firefly

Energy's Oasis Pb–acid battery [25] utilizes patented Microcell™ foam technology that is designed for deep-cycle applications, too. The negative electrode, which is heavy lead metal, is replaced by a lightweight negative electrode with the carbon–graphite foam structure. This reduces lead in the system by *ca.* 50%. It eliminates sulfation and prolongs reserve capacity minutes (RCMs). The battery life increases while it is cycled in deep charge/discharge applications (800 cycles at 80% DoD). The future work on newly structured Pb–batteries is necessary for examination of basic battery chemistry and improved electrode processes, exploration of mass transfer limitations, and investigation of the failure mode or mechanisms.

Election of suitable battery chemistry is critical for a specific power reserve application. Active material, utilization of active material, support structure, current collector, separator, electrolyte, and battery system maintenance (gas recombination and thermal management) are important factors for battery performance, state-of-health (SoH), and operating life-cycle time. Lead–acid batteries have been applied to provide automobile reserve power for SLI applications nearly more than a 100 years. The simple reasons are this type of battery offering the best cost/performance ratio of all batteries [26]. The lead–acid battery also has a wider operating temperature range than other batteries. Traditional flooded batteries have been used without any special control under harsh conditions for automotive applications. At a later time, the VRLA (valve-regulated lead–acid) batteries were manufactured with gas recombination capability, *i.e.* oxygen from the positive electrode is reduced on the negative electrode surface. Its internal pressure is maintained using safety valves. Further advanced battery design concepts and structure improvements give birth to the above mentioned ultrabattery and Oasis Pb–acid battery. The novel battery designs and technical improvement will greatly promote its potential high-rate and deep-cycle applications.

Some forms of sustainable electricity generation are variable according to the changeable energy sources. For example, electricity from sunlight is available while the sun shines and wind-generated electricity is only available while the wind blows. This requires that reserve power sources must be available at short supply of energy sources – when clouds shade the solar collectors, and/or when the wind slows [27]. Many energy storage systems still rely on battery storage, but storing large amounts of electricity in batteries has not been put to general use. Although batteries are normally expensive and have limited life-cycle time, battery energy storage for reserve power application has relatively high efficiency, up to 90% or even better. Currently, various applications for energy storage require that batteries with proper deep-cycle capacity and high-rate response capability. It is no doubt that further advancement of lead–acid batteries, with high-rate durability and deep-cycle capability as well as acceptable life-time, will have great potentials in future power reserve and energy storage applications, either in EVs/HEVs or sustainable electricity storage systems.

4. Conclusion

Four different lead–acid batteries were collected and tested via *ac* impedance. The battery features of various frequency loops were analyzed for better understanding of the battery's state-of-health. Non-destructive analysis was performed on a defective battery and a failed Pb–acid battery. In most of energy storage and vehicle applications, there are deep-cycle long-life requirements for lead–acid batteries. Battery capability of HRPSoc use and compat-

ible cycle-life are also essential for future HEV applications. The impedance technique is a helpful tool for testing and analysis of different lead–acid batteries. It is also useful for understanding the features of novel structure design. Many efforts on the lead–acid battery and its structure design make the long-history Pb–acid battery a strong competitor for the potential vehicle and power reserve applications versus other advanced battery systems, such as Ni–MH or Li-ion battery systems. This is because of its lower materials cost, less battery maintenance requirement, and its existing economic recycle system.

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